User Localization for Rescue Operations Exploiting the Cross-Cross-Correlations of Signals from Multiple Sensors

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***Abstract*—Delay estimation of incoming signals in passive systems is still nowadays at the base of many signal processing applications ranging from passive radars to underwater acoustics, indoor acoustic positioning, and others. This paper aims at improving the estimation of the delays with respect to multiple sensing nodes for user localization for rescue operations under the unavailability of the base stations in the area of interest. To this end, it suitably exploits a method grounded on the computation of the cross-correlation between the cross-correlation estimates (say cross-cross-correlation) of the received signals. The estimation problem is formulated as a least squares (LS) optimization problem. As a consequence, the proposed method inherits an important feature of the LS approach, namely that is independent of the underlying data distributions. The performance assessment is conducted in comparison with its classic counterpart.**

***Index Terms*—Cross-cross-correlation, delay estimation, time difference of arrivals (TDOA), user localization.**

I. Introduction

User localization in disaster or under critical situations is an operation of paramount importance. In fact, it allows rescue teams to intervene in a timely manner in order to save as many lives as possible. In such difficult situations, environmental as well as psychological factors might prevent the users from making a call or transmitting their location or there are situations of unavailability of the surrounding base stations (BSs). In the second case, a passive localization based on the time difference of arrival (TDOA) of the signals spontaneously emitted by the user equipment and received by sensing nodes specifically deployed in the area of interest (such as unmanned aerial vehicles) can represent an effective countermeasure. Conversely, in normal situations (i.e., with BSs correctly operating), in place of deploying sensors, many localization services can be effectively used, e.g., received signal strength (RSS), time-of-arrival (TOA), angle-of-arrival (AOA) or jointly combinations of them. The interested reader is referred to [1]–[3] for further details.

In the aforementioned critical situations, the hyperbolic positioning is performed by exploiting the TDOAs between the signals emitted by the user and received at more than one sensing node. This task can be effectively solved by resorting to many algorithms developed over the years, viz. [4]–[6]. It is now worth underlining that the above procedures utilize as starting point accurate estimates of the delay or TOA of the signals recorded at each receiver. Generally, this task can be accomplished by evaluating the cross-correlation between a couple of signals and estimating their respective delay as the time instant that maximizes the cross-correlation function. This classic estimation procedure can be also improved by filtering the intercepted signals before the evaluation of the cross-correlation leading to the so-called generalized cross-correlation (GCC) [7]–[11]. To overcome the major limitation of the GCC that is due to the availability of a priori information on the signal and noise spectra, in [12] a new delay estimation method for TDOA-based passive radar target localization has been derived and tested. Such a technique utilizes the cross-cross-correlation (i.e., the cross-correlation between each couple of cross-correlations performed on the received signals) to obtain the delay estimates by solving a least squares (LS) optimization problem. In this paper, we apply the method of [12] to accurately estimate the signal delays in a multi-receiver noncooperative localization for rescue operations. The numerical examples are obtained by considering 5G signal transmissions and show the effectiveness of the cross-cross-correlation in correctly estimating the involved delays before localization.

II. Problem formulation and delay estimation

Let us consider a hazardous scenario that has caused disruption to the communication network, with BSs out of order. To search for individuals who are missing or in danger, a total of M mobile sensors, e.g., in the form of terrestrial or flying drones, are assumed to be deployed in the area of interest, as shown in Figure 1.

These sensors are capable of identifying the location of user equipment attempting to transmit signals as specified in the following. Each node receives a delayed copy of the signal transmitted by the source (or target) to be localized. Then, the reference node processes all the received signals to provide an estimate of the target position starting from the delay estimates. Therefore, indicating with $s(t)$ the random signal transmitted by the user equipment, the signal received at the i-th sensing node can be described by means of the following equation

$$r_i(t) = \alpha_i s(t - t_i) + w_i(t),\ i = 0, \dots, M-1, \quad (1)$$

where $\alpha_i \in \mathbb{C}$, $i = 0 \dots, M-1$, is a complex unknown scaling factor accounting for transmitting power, channel propagation effects, as well as the distance between the transmitter

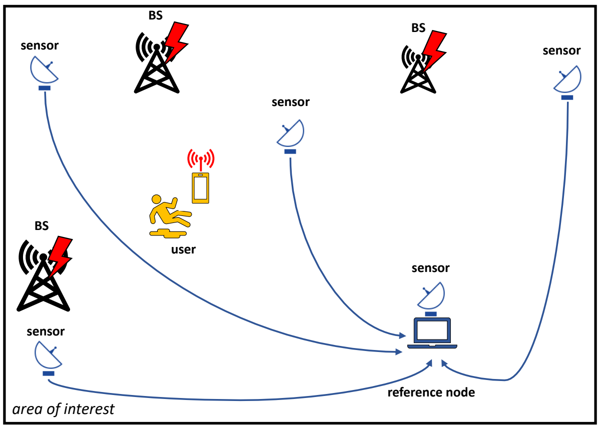


Figure 1. Operating scenario where the user is in a critical situation with BSs out of order, and the surrounding sensing nodes that acquire the emitted signals to localize the user equipment.

and the i-th sensing node.[1] Finally, $w_i(t)$, $i = 0\ldots, M-1$, is the interference component that is assumed to be uncorrelated with the signal. Additionally t_i, $i = 0\ldots, M-1$, indicates the time delay or TDOA at each receiving node to be estimated, evaluated with respect to the delay of the first sensing node, say t_0, assumed in the following, without loss of generality, equal to 0 s.

A. Cross-correlation based delay estimation

Let us consider a couple of sensors indexed by integers i and j, and let us indicate with $R_{ij}(\tau)$ an estimate of their cross-correlation, with τ being the delay variable. Then, the delay difference between the two signals can be obtained as the value maximizing the cross-correlation magnitude, that is

$$\hat{\tau}_{ij} = \arg\max_{\tau} \left\{ |R_{ij}(\tau)| \right\}, \tag{2}$$

where $|\cdot|$ is the modulus of the input argument.

Now, considering the pairs of integers indexing all the sensing nodes, namely (i, j), $i, j = 0, \ldots, M-1$ ($j > i$ to remove redundancies), all the cross-correlation maxima can be properly used to estimate the relative signal delays acquired by the M sensing nodes, viz. $\tau_{ij} = t_i - t_j$. Then, it is possible to estimate the $M-1$ delays solving the following overdetermined system of Q equations (with $Q = 1/2\left(M^2 - M\right)$ [12])

$$\boldsymbol{A}\boldsymbol{t} = \hat{\boldsymbol{\tau}}, \tag{3}$$

where

$$\boldsymbol{t} = \begin{bmatrix} t_1 \\ \vdots \\ t_{M-1} \end{bmatrix}, \qquad \hat{\boldsymbol{\tau}} = \begin{bmatrix} \hat{\tau}_{01} \\ \vdots \\ \hat{\tau}_{(M-2)(M-1)} \end{bmatrix},$$

and $\boldsymbol{A}$ is the $Q \times (M-1)$ model matrix whose expression is provided in [12]. Finally, (3) is solved by means of the LS approach, namely

$$\hat{\boldsymbol{t}} = \boldsymbol{A}^{+}\hat{\boldsymbol{\tau}}, \tag{4}$$

with $(\cdot)^{+}$ the pseudo-inverse of its matrix argument.

B. Cross-cross-correlation based delay estimation

Beyond the classic cross-correlation, the method presented in this section allows us to improve the delay estimation when $M > 2$ receiving nodes are available. The method is based on the use of the cross-cross-correlation estimate, $C_{ijlm}(\delta)$, defined as the cross-correlation between the cross-correlations $R_{ij}(\tau)$ and $R_{lm}(\tau)$, that is

$$C_{ijlm}(\delta) = \frac{1}{2T}\int_{-T}^{T} R_{ij}(\tau)R^{*}_{lm}(\tau - \delta)d\tau, \tag{5}$$

with δ the lag variable, T the observation time, and $(\cdot)^{*}$ denoting the conjugate operator. Additionally, the number of equations is improved further by involving in the system also a flipped version of the cross-cross-correlation estimate, $F_{ijlm}(\delta)$, defined as the convolution between the two cross-correlations, namely

$$F_{ijlm}(\delta) = \frac{1}{2T}\int_{-T}^{T} R_{ij}(\tau)R_{lm}(\delta - \tau)d\tau. \tag{6}$$

It can be shown that the resulting overdetermined system results to have $L = (1/4)M^4 - (1/2)M^3 - (1/4)M^2 + (1/2)M$ equations [12], with $L > Q$.

Now, using a compact matrix notation the problem at hand can be cast as

$$\boldsymbol{B}\boldsymbol{t} = \hat{\boldsymbol{\delta}}, \tag{7}$$

where

$$\boldsymbol{t} = \begin{bmatrix} t_1 \\ \vdots \\ t_{M-1} \end{bmatrix}, \qquad \hat{\boldsymbol{\delta}} = \begin{bmatrix} \bar{\delta}_{0102} \\ \vdots \\ \bar{\delta}_{(M-3)(M-1)(M-2)(M-1)} \\ \breve{\delta}_{0102} \\ \vdots \\ \breve{\delta}_{(M-3)(M-1)(M-2)(M-1)} \end{bmatrix},$$

and $\boldsymbol{B}$ is the $L \times (M-1)$ model matrix whose structure is detailed in [12] and is composed by many zero entries with the others that assume only ± 1 and ± 2 values. Moreover, the delay estimates $\bar{\delta}$ and $\breve{\delta}$ are derived as the values maximizing the peak of the cross-cross-correlation and its flipped version, that should be at the index $t_i - t_j - t_l + t_m$ and $t_i - t_j + t_l - t_m$, respectively, namely

$$\bar{\delta}_{ijlm} = \arg\max_{\delta} \left\{ |C_{ijlm}(\delta)| \right\}, \tag{8}$$

and

$$\breve{\delta}_{ijlm} = \arg\max_{\delta} \left\{ |F_{ijlm}(\delta)| \right\}. \tag{9}$$

As before, the LS solution to (7) is computed, namely

$$\hat{\boldsymbol{t}} = \boldsymbol{B}^{+}\hat{\boldsymbol{\delta}}. \tag{10}$$

Before concluding this section, it is worth mentioning that the equations in the problems (3) and (7) can be also

[1]In this paper, for sake of simplicity, we do not assume the presence of multipath in the considered signal model. However, it is worth to underline that multipath will produce a model mismatch that will be reflected into a performance degradation of the proposed solution. Therefore, in future works, it would be interesting to incorporate also the multipath effect in the considered signal model.

jointly combined to form another version of the considered algorithm, that is

$$\boldsymbol{C}\boldsymbol{t} = \hat{\boldsymbol{\xi}}, \tag{11}$$

where

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{A} \\ \boldsymbol{B} \end{bmatrix} \quad \text{and} \quad \hat{\boldsymbol{\xi}} = \begin{bmatrix} \hat{\boldsymbol{\tau}} \\ \hat{\boldsymbol{\delta}} \end{bmatrix},$$

whose LS solution is again derived from the application of the pseudo-inverse of $\boldsymbol{C}$, i.e.,

$$\hat{\boldsymbol{t}} = \boldsymbol{C}^{+}\hat{\boldsymbol{\xi}}. \tag{12}$$

III. Study Cases

In this section, the cross-cross-correlation method is applied in the context of rescue operations simulating 5G signals. The figure of merit is the root mean square error (RMSE) of the estimated times computed through Monte Carlo counting techniques over $M_c = 10^3$ independent trials. Specifically, we use the following estimator

$$\text{RMSE} = \sqrt{\frac{1}{M_c}\sum_{m=1}^{M_c} \left\|\hat{\boldsymbol{t}}_m - \boldsymbol{t}_m\right\|^2}, \tag{13}$$

where $\|\cdot\|$ is the Euclidean norm, $\hat{\boldsymbol{t}}_m$ and $\boldsymbol{t}_m$ are the vectors containing the estimated and true time delays at the m-th Monte Carlo trial, respectively.

As to the signal received at each sensing node, it is generated as the baseband waveform of a 5G physical uplink shared channel (PUSCH) fixed reference channel (FRC) transmitted signal following the 3GPP 5G NR standard that defines configurations for the purposes of conformance testing [13]. For each received signal it is also fixed $\alpha_i = 1$ and varying the noise power so as to have a signal to noise ratio (SNR) of 3 dB. The other parameters of the transmitted signal are: channel bandwidth 5 MHz, OFDM with subcarrier spacing 15 kHz, and QPSK modulation, sample frequency $f_s = 1/t_s = 7.68$ MHz. However, to reduce the computational burden, only the first 1000 samples are extracted from the entire signal for the next tests. The magnitude (for a duration of 25 μs) and constellation of the QPSK baseband waveform are reported in Figure 2 to provide a visual inspection of the effect of the injected noise on the considered signal. Finally, since in these study cases M receivers are considered, the $M-1$ delays have been randomly selected at each Monte Carlo trial. More precisely they have been selected as a realization of a uniform random variable within the interval $[0, t_s]$.

The examples illustrated in this section provide the comparison of the considered cross-cross-correlation based method (indicated with CCC in the following) with the classic cross-correlation (shortly CC in what follows). Moreover, the technique based on the exploitation of jointly all the CC and CCC equations is considered in the plots (indicated as CCC2). Hence, Figure 3 shows the RMSE (expressed both in ns and in m) versus the number of available receivers for the scenario described above. From the figure inspection, as expected, it is evident that increasing the number of sensing nodes provides a better and better delay estimation, with the RMSE that tends to continuously reduce. This fact is essentially due to the higher number of available equations in the LS problem when a higher number of sensing nodes is under consideration.

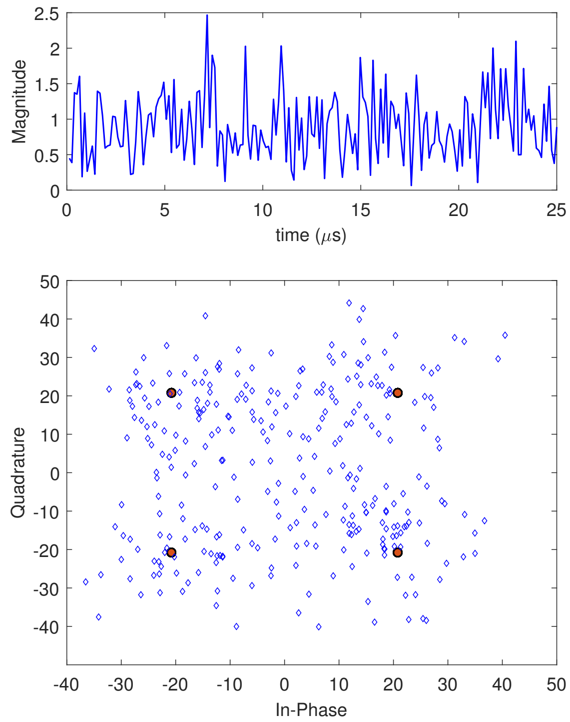


Figure 2. Magnitude (for a duration of 25 μs) and constellation of NR-FR1-TM 3.2 QPSK baseband waveform with SNR = 3 dB.

All estimators benefits from this behavior, even though the both CCC and CCC2 provides almost the same performances, gaining over the classic CC. Nevertheless, in this specific situation, the CCC2 slightly loses with respect to the CCC because of the more erroneous equations in the CC formation.

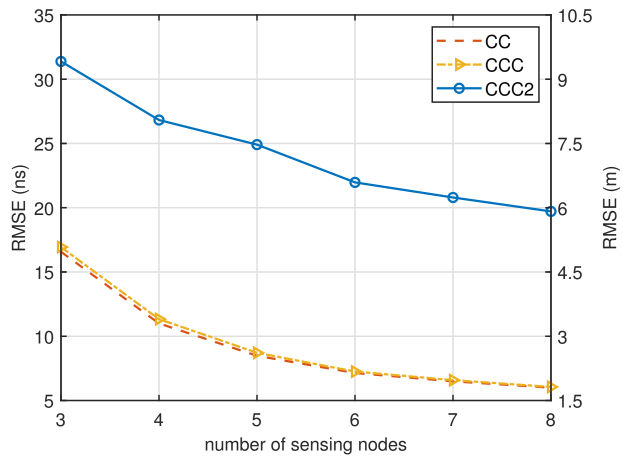
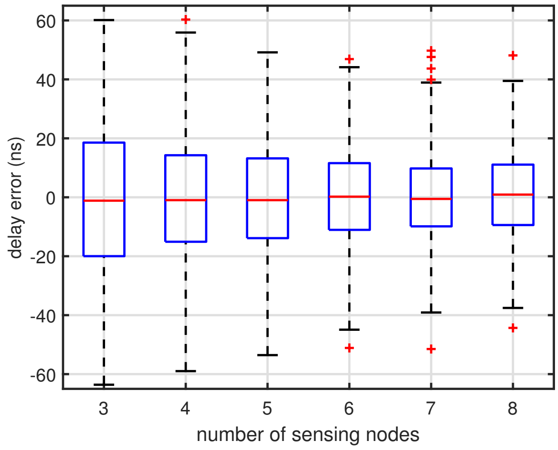
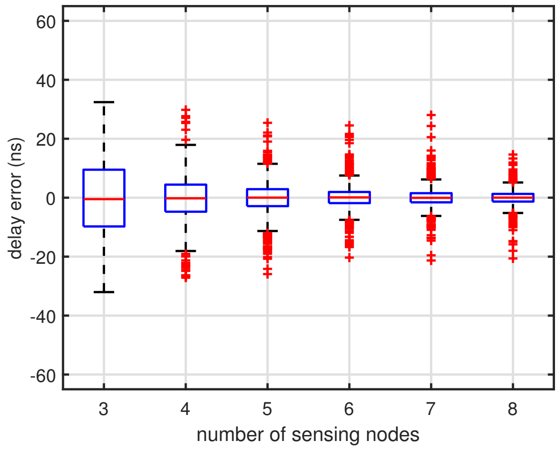


Figure 3. RMSE (expressed both in ns and in m) of the delay estimate versus number of receiving sensing nodes M.

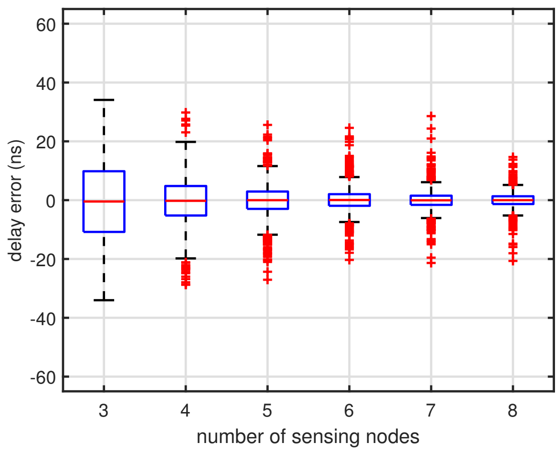
To corroborate further with the analysis of Figure 3, in Figure 4 the boxplots of the delay estimation error for the CC, CCC, and CCC2 are represented as function of the number of available nodes. Each boxplot reports the median value together with the 25th and 75th percentiles (i.e., the edges of the box), whereas points marked as + indicate outliers. The boxplots also show the effectiveness of the considered cross-cross-correlation method in accurately estimating (with a reduced dispersion around the median) the delays also with a reduced number of sensing nodes, overcoming the classic CC.



(a) CC



(b) CCC



(c) CCC2

Figure 4. Boxplots of the delay estimation errors versus number of sensing nodes. Subplots refer to a) CC, b) CCC, and c) CCC2.

IV. Conclusions

This paper has addressed the problem of user localization in the course of rescue operations. To this end, we have applied the cross-cross-correlation method for delay estimation of the signals acquired at multiple sensing nodes. More precisely, the simulated scenario consisted of a 5G user transmitting the PUSCH FRC signal whose replicas are intercepted by multiple sensors for the passive localization process. Tests have been conducted considering as figure of merit the RMSE of the delay estimates and the boxplots of the estimation error. Results have demonstrated the advantages of using the cross-cross-correlation based method with respect to its classic counterpart that exploits the cross-correlation only.

References

[1] P. Rawat, M. Haddad, and E. Altman, "Towards Efficient Disaster Management: 5G and Device to Device Communication," in *2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*. IEEE, 2015, pp. 79–87.

[2] S. Bartoletti, A. Conti, D. Dardari, and A. Giorgetti, "5G Localization and Context-Awareness," in *5G Italy White Book: From Research to Market*. National, Inter-Univ. Consortium for Telecommunications, 2018, pp. 167–187.

[3] C. Laoudias, A. Moreira, S. Kim, S. Lee, L. Wirola, and C. Fischione, "A Survey of Enabling Technologies for Network Localization, Tracking, and Navigation," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3607–3644, 2018.

[4] K. C. Ho and W. Xu, "An Accurate Algebraic Solution for Moving Source Location using TDOA and FDOA Measurements," *IEEE Transactions on Signal Processing*, vol. 52, no. 9, pp. 2453–2463, 2004.

[5] M. Malanowski and K. Kulpa, "Two Methods for Target Localization in Multistatic Passive Radar," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 1, pp. 572–580, 2012.

[6] M. Cobos, F. Antonacci, L. Comanducci, and A. Sarti, "Frequency-Sliding Generalized Cross-Correlation: A Sub-Band Time Delay Estimation Approach," *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 28, pp. 1270–1281, 2020.

[7] C. Knapp and G. Carter, "The Generalized Correlation Method for Estimation of Time Delay," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 24, no. 4, pp. 320–327, 1976.

[8] P. Schultheiss, "Locating a Passive Source with Array Measurements: a Summary of Results," in *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, vol. 4. IEEE, 1979, pp. 967–970.

[9] A. Quazi, "An Overview on the Time Delay Estimate in Active and Passive Systems for Target Localization," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 29, no. 3, pp. 527–533, 1981.

[10] L. Miller and J. Lee, "Error Analysis of Time Delay Estimation using a Finite Integration Time Correlator," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 29, no. 3, pp. 490–496, 1981.

[11] M. Azaria and D. Hertz, "Time Delay Estimation by Generalized Cross Correlation Methods," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 32, no. 2, pp. 280–285, 1984.

[12] L. Pallotta and G. Giunta, "Accurate Delay Estimation for Multisensor Passive Locating Systems Exploiting the Cross-Correlation Between Signals Cross-Correlations," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 3, pp. 2568–2576, 2022.

[13] 3GPP TS 38.104, *NR; Base Station (BS) Radio Transmission and Reception*, 3rd Generation Partnership Project (3GPP); Technical Specification (TS) Group Radio Access Network. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/38_series/38.104